OPTO-ELECTRONIC OSCILLATOR AND ITS APPLICATIONS

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ABSTRACT

We present the theoretical and experimental results of a new class of microwave oscillators called opto-electronic oscillators (OEO). We discuss techniques of achieving high stability single mode operation and demonstrate the applications of OEO in photonic communication systems.

INTRODUCTION

Traditional microwave oscillators cannot meet all the requirements of photonic communication systems which require high frequency and low phase noise signal generations. Because photonic systems involve signals in both optical and electrical domains, an ideal signal source should be able to provide high frequency signals in both optical and electrical domains. In addition, it should be possible to synchronize or control the signal source by both electrical and optical references.

We have reported such a signal source[1,2] that converts continuous light energy into stable and spectrally pure microwave signals. This Opto-Electronic Oscillator, OEO, consists of a pump laser and a feedback circuit including an intensity modulator, an optical fiber delay line, a photodetector, an amplifier, and a filter, as shown in Fig. 1. Its oscillation frequency, limited only by the speed of the modulator, can be up to 75 GHz.[3]

PROPERTIES OF OEO

Our studies[2] have shown that the OEO has the following important properties:

1) The OEO has an electrical output port and an optical output port to provide a microwave signal and a modulated optical signal simultaneously, eliminating the costly and high loss electrical-to-optical and optical-to-electrical conversions for the users.

2) in addition to have an electrical injection port for locking the OEO to a local reference signal, the OEO has an optical injection port for injection locking the OEO to a remote reference signal, making it simple to integrate the OEO in a photonic communication system.

3) The OEO is a voltage controlled oscillator (VCO) whose oscillation

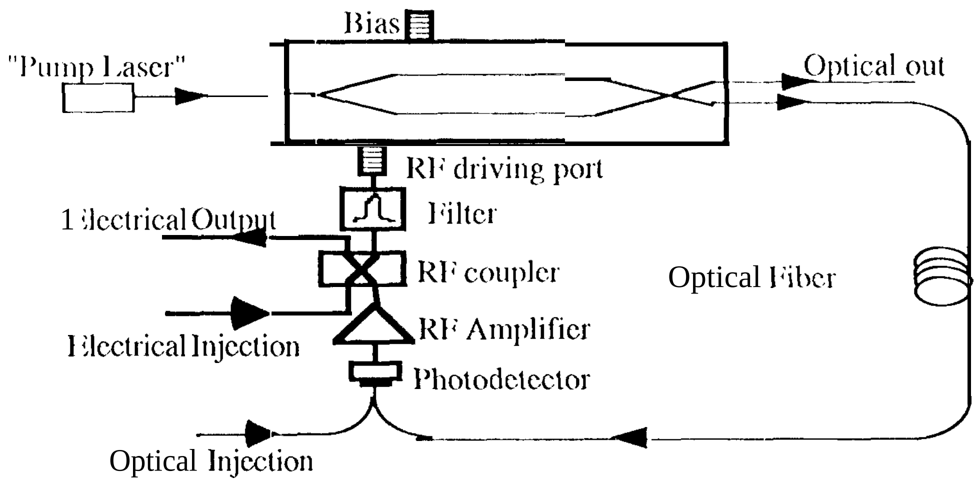

Fig. 1 Device description of the OEO

frequency can be tune by applying a volt age to the bias port of the E/O modulator or to a PZT fiber stretcher.

4) No amplifier in the loop is needed if the optical power of the pump laser is high enough so that $I_{ph}R \geq V_{\pi}/\pi$ is satisfied, where I_{ph} is the received photocurrent in the photodetector, R is the load resistance of the receiver, and V_{π} *is the* half-wave voltage of the modulator. The elimination of the amplifier in the loop eliminates the amplifier noise, resulting in a more stable oscillator.

5) The oscillation frequency is $f_{osc} = (k+1/2)/\tau$ or $f_{osc} =$ k/7, depending on the bias, where k is an integer, representing different possible oscillating modes, τ is the total group delay of the loop. For a Mach-Zehnder modulator based OEO, the oscillation amplitude is approximate.d as

$$V_{osc} = (2\sqrt{2}\,V_{\pi}/\pi)\sqrt{1 - 1/|G_S|} \qquad (1)$$

where $|G_S|$ is the open loop small signal gain of the 01X].

6) The phase. noise spectrum is:

$$S_{RF}(f') = \frac{\delta}{(\delta/2\tau)^2 + (2\pi)^2(\tau f')^2}$$

for $2\pi f' \mathrm{T} << 1$ (2.)

where f' is the frequency offset from the oscillation frequency f_{osc} and δ is the noise to signal ratio of the OEO and is defined as:

$$\delta = \rho_N G_A^2 / P_{osc}$$
$$= [4k_B T(NF) + 2eI_{ph}R + N_{RIN} I_{ph}^2 R] G_A^2 / P_{osc} \qquad (3)$$

In Eq. (3) P_{osc} is the oscillation power of OEO and ρ_N is the total noise densit y input to the oscillator which equals to the sum of the thermal noise, the shot noise, and the laser's relative intensity noise (RIN) densities. in Eq. (3), k_B is the Boltzman constant, 7' is the ambient temperature, NF is the noise factor of the RF amplifier, e is the electron charge, and N_{RIN} is the RIN noise of the pump laser.

It is evident from Eq. (3) that the phase noise of the OEO decreases quadratically with the frequency offset from the oscillation frequency, as shown in Fig. 2a. For a fixed frequency offset, the phase noise decreases quadratically with the loop delay time, as indicated in Fig. 2b. For large enough loop delay and strong enough optical pump power, the phase noise approaches relative intensity level of the laser, below -140 dBc/Hz at 10 kHz for a Mach-Zehnder modulator based 0110.

7) The OEO's phase noise is independent of the oscillation frequency f_{osc}. This result is significant because it allows the generation of high frequency and low phase noise signals with the OEO. On the contrary, the phase noise of a signal generated using frequency multiplying methods generally increases quadratically with the frequency.

COMPARISON 011'1)11'1'10<1 ;NT TY}']:S 01?01 :O

Although the OEO in Fig. 1 is made of a a Mach-Zehnder modulator, any type of intensity modulators, such as electro-absorption modulator, directional coupler modulator, electro-acoustic modulator, or even a di rectl y modulate.d diode laser[4] can be used to construct the OEO. However, d ifferent OEOs const ructed using different modulators have different size, power requirement, stabilit y, phase noise, maximum oscillation frequency, and dependence on noise sources. We compare the performance of the.se OEOs and find their advantages and limitations. We further investigate laser's RIN noise, ampl i fiers 1/f noise, fiber length fluctuation caused by thermal fluctuation and acoustic fluctuation, fiber's nonlinearity and dispersion on the stability and spectral purity of different t ype 01 'm. 'The resu lts of these investigations will be presented at the conference.

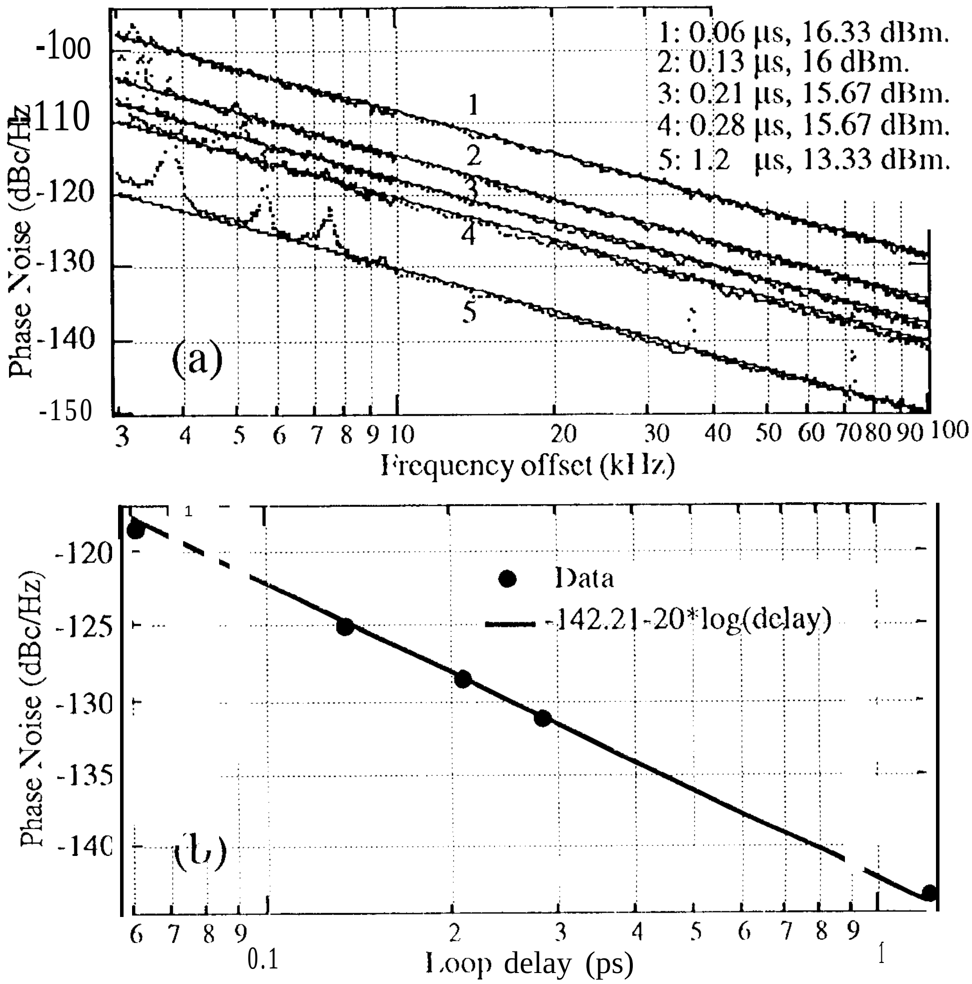

Fig. 2 Single side band phase noise of an OEO measured at 800 MHz. (a) Measured phase noise spectra at different loop delays and their fits to Eq. (2), (b) Phase noise at 30 kHz offset from the center frequency as a function of loop delay.

TECHNIQUES FOR SINGLE MODE SELECTION

In an OEO, single mode selection is an important issue. We have shown that long feedback loop in an OEO results in a lower phase noise. However, longer loop also cause the mode spacing of the OEO to be small, making single mode selection difficult.

We present here a multi-loop technique that permits the OEO to operate in a single mode while having a long loop length, resulting in a reduced phase noise. It relaxes the requirement of bandwidth or eliminates the need of a RF filter in the loop, making the oscillator widely tunable. Furthermore, it reduces the oscillation threshold of the OEO by as much as 6 dB, making it easier to realize an OEO without employing a RF amplifier. We also discuss other techniques for effective single mode selection and compare their advantages and short comings.

APPLICATIONS

Voltage Controlled Oscillator. As mentioned earlier, the OEO is a special VCO with optical as well as electrical output. Therefore it can perform al 1 functions that a VCO is capable of for microwave photonic systems.

Photonic Signal Mixing. The0110 can also be used for photonic signal up/down conversion. For such an application, a stable optical RF LO, or a modulated optical signal at a RF frequency, is required. The OEO can accomplish just that, since one of its outputs gives the RF oscillation in optical domain.

Carrier Distribution. Because the OEO can be injection locked by a remote optical signal, it can be used for high frequency RF carrier regeneration, amplification, and distribution. Such a capability is important in large microwave photonic systems.

Frequency multiplication. The injection locking property of the OEO can also be used for high gain frequency multiplication. Wc used subharmonic injection locking technique and demonstrated phase-locking the oscillator operating at 300 MHz to a 100 MHz reference of 4 dBm. The output of the oscillator is 15 dBm, resulting in a gain of 11 dB and frequency multiplication factor of 3. Wc will also discuss frequency multiplication using laser diodes nonlinearity. In this scheme, the OEO is tuned to operate at a nominal frequency close to the nth harmonic Of the reference signal driving the laser diode. Upon the injection of the laser's output, the OEO will be locked to the. nth harmonic. This scheme offers remote frequency multiplication capability and may be useful for many microwave photonic systems.

Comb Frequency and Pulse Generation. The OEO can also be used to generate frequency combs and square pulse. For this application, the OEO is chosen to operate with multimodes. A sinusoidal signal with a frequency equal to the mode spacing or a multiple of mode spacing is injected into the oscillator. Just like laser mode-locking, this injected signal will force all modes to oscillate in phase. Consequently, wc obtain a comb of frequencies that arc in phase. in the time domain, the output signal is square pulses.

Clock and carrier recovery. The same injection locking property of the OEO can also be used for clock and carrier recovery. Wc have demonstrated clock recovery at 100 Mb/s and 5Gb/s, and obtained excellent results. Data rates up to 75 Gb/s can also be recovered using the injection locking technique with an OEO operating at 7S GHz. Another important feature of the OEO technique is that the clock can be recovered directl y from data just out of a fiber optic transmission line, without the need of optical to electrical conversion. In addition, the recovered clock signal has both optical and electrical forms and is easy to interface with a fiber optic communication system.

Similar to clock recovery, a carrier buried in noise can also be recovered by the OEO. Wc have also demonstrated the recovery of carrier from noise and increased carrier to noise ratio by 50 dB.

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